Combined Hydrological and Geologic Assessment for Sustainable Management of the Sambunotan Watershed, Dinagat Islands, Philippines

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Abstract: *This paper presents a combined hydrological and geological study to support the Sambunotan Watershed Management Plan (SWMP) for Tubajon and Loreto in the Dinagat Islands, Philippines. The primary objective is to integrate the results of the geological assessments with hydrological assessment data to provide a better understanding of the watershed's dynamics to support the development of the SWMP. Utilizing GIS tools and IfSAR DTM, the watershed's precise boundaries, covering 2,819.9125 hectares, were established. Hydrological modeling using HEC-HMS, calibrated with field data, achieved a "Very Good" performance, with a Nash-Sutcliffe efficiency of 0.85. The computed annual baseflow volume is 71,601,871.66 m³, wherein 73.69% is generated during the wet season. Geological assessments revealed that the river networks are influenced by harzburgite and basalt rocks, confirmed through field surveys identifying harzburgite, pillow basalts, and clastic sediments. Regions with clastic sediments and limestone, identified as potential aquifers, are recommended for further groundwater exploration.*

Keywords: Sambunotan, Watershed Management, Hydrological Modeling, Geologic Assessment

1. INTRODUCTION

Watersheds are critical for maintaining ecological balance, providing essential water resources for agricultural, domestic, and industrial uses, and supporting diverse ecosystems. When maintained healthy, watersheds can provide valuable services to society, including providing and purifying fresh water [1,2]. Globally, effective watershed management has become increasingly important due to the pressures of climate change, population growth, and economic development [3].

The Sambunotan watershed, as shown in Fig. 1, is geographically located in the municipalities of Tubajon and Loreto in the Province of Dinagat Islands in Caraga Region, Mindanao, Philippines. Sambunotan watershed supplies drinking water to six barangays in Tubajon, Dinagat Islands. It also provides agriculture irrigation water and supports threatened and endemic plant and animal species [4].

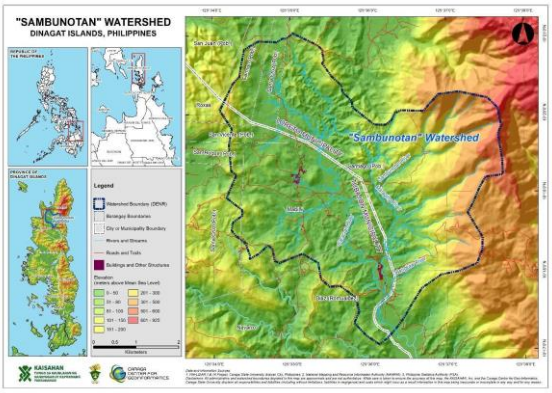

Fig. 1. Map of the Sambunotan Watershed with its boundary delineated using a Digital Terrain Model (DTM) with the aid of a Geographic Information System (GIS).

With the increasing water demand and the threat of land cover conversion due to several approved mining operation permits in the area, there is a need to develop and implement robust, sustainable management strategies to protect the watershed's resources, ensure the availability of clean water, and preserve the ecological integrity of the watershed. With this, the Province of Dinagat Islands crafted its 5-year Dinagat Islandscape Development Framework and Strategies through a collaborative effort among Municipal and Provincial Local Government Units with civil society organizations Kaisahan Tungo sa Kaunlaran ng Kanayunan at Repormang Pansakahan Inc. (KAISAHAN), Philippine Association for Intercultural Development (PAFID), Conservation International Philippines (CIP), and Forest Foundation Philippines (FFP). To realize the Islandscape Framework, KAISAHAN, PAFID, and FFP piloted the development of the Sambunotan Watershed Management Plan.

This paper presents the results of the combined hydrological and geological study conducted to support the development of the Sambunotan Watershed Management Plan. Integrating geological assessments with hydrological studies aims to better understand the watershed's dynamics. While hydrological data offers insights into water flow, volume, and seasonal variations, geological assessments reveal the underlying lithological and structural controls that influence these hydrological patterns [5]. By examining the geological composition, the study aims to identify areas of high porosity and permeability, which are crucial for groundwater exploration. This combined approach is envisioned to enhance the accuracy of hydrological models and support the development of more effective and sustainable watershed management strategies, ensuring the protection and optimal use of the Sambunotan watershed's resources.

2. MATERIALS AND METHODS

To conduct the hydrological and geologic assessment, we generated a precise watershed boundary and established baseline hydrological data. The results of the hydrological analysis conducted by Albores et.al [4] were used in this study. As elaborated in their report, the field data were collected for hydrologic model calibration, generated hydrograph results, and computed baseflows during wet and dry seasons. This analysis was used to assess the current water resource availability and support improved water management decisions by validating visions, scenarios, and strategies for the sustainable management of the watershed. All available lithologic maps with lineaments of the watershed were used for the geologic assessment. Field data gathering was conducted to validate these geologic maps to ensure accuracy.

2.1 Hydrological Assessment

GIS-based Watershed Boundary Delineation

The GIS-based watershed boundary delineation was carried out to generate a more precise boundary by harmonizing GIS tools with the watershed boundary delineated by the Department of Environment and Natural Resources (DENR). This process mainly utilized Interferometric Synthetic Aperture Radar (IFSAR) Digital Terrain Model (DTM) and drainage network derived using Light Detection and Ranging (LiDAR) data to delineate the GIS-based watershed boundary.
The delineation process starts with sub-setting the IfSAR DTM, which initially contains the municipalities of Loreto and Tubajon, to the portion where the Sambunotan Watershed is located based on the buffered, DENR-delineated watershed boundary. The DTM subset was then subjected to sink filling and reconditioning to create a hydrologically correct DTM. This means that sinks in the DTM are filled, and the actual drainage network is "burned" or embedded into the DTM. This procedure is required to delineate the watershed boundary more accurately.

Applying the "D8" flow method or algorithm to the hydrologically correct DTM subset created a flow direction raster. The D8 flow method determines the flow direction from each cell in the DTM to its steepest downslope neighbor [6].

Using the flow direction raster and approximate location of the watershed boundary (based on the intersection of the DENR-delineated watershed boundary and the drainage network in the downstream-most portion), a watershed raster was then generated. This was then converted into a polygon vector file representing the GIS-delineated watershed boundary. The area of this watershed boundary was calculated and compared to the watershed area based on the DENR-delineated boundary. For the GIS-delineated boundary to be deemed final/acceptable, the GIS-delineated area must be as close as possible to that of the DENR. In the first delineation attempt, this was not achieved such that the outlet of the watershed was adjusted, and the delineation procedure was repeated until the area was closest to that of DENR. After several attempts, we generated the final watershed boundary with an area of 2,819.9125 hectares.
This boundary was then used to determine which municipalities and barangays are located within the watershed, including the percentage composition of their land areas. For this purpose, we utilized the barangay boundaries from the Philippine Statistical Authority and the National Mapping and Resource Information Authority (NAMRIA).

Hydrological Measurements

The hydrological measurements involve the following: river cross-section at discharge points, water surface elevation, rainfall, water level, and discharge. We adapted the method employed by Santillan et al., 2019 [7].

The real-time kinematic (RTK) method was employed using two Global Navigation Satellite System (GNSS) receivers to determine the cross-section profile of the discharge point and water surface elevations, reference to EGM 2008. RTK surveying achieves centimeter-level precision and involves a rover and a base station. The base station, a static point with known coordinates, computes the error using GNSS by comparing it to its precise location and then transmitting corrections to the rover in real-time.

The rainfall, water level, and discharge measurements were conducted in the project area to develop a hydrological model, calibration, and validation. Rain gauges, a water level logger, 2D velocity meters, and an Acoustic Doppler Current Profiler (ADCP) were installed to capture low and high flows. At least one rain gauge was installed upstream of the watershed to capture rain during the same period with other deployed sensors. A river cross-section was measured at each deployment station so that the discharge rate at any given time, t, can be computed using $Q = VA$ where Q = discharge, V= water velocity, and A = cross-sectional area. The water level and computed discharge will also be used to generate rating curves, which will be useful later in forecasting water levels.

Rating curves, also called H-Q Curves, were derived using the computed discharge and measured water level at each deployment station. This curve gives the relationship between the measured water levels and the discharge of the river basin at this location.

Hydrological Modeling

Hydrological modeling involves developing the HEC HMS model, calibration, and performance evaluation.
The hydrological analysis utilized the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS). This model examines hydrological characteristics and simulates surface hydrological processes. The model can also forecast the hydrological conditions of an area depending on various inputs such as precipitation, land use, soil characteristics, and topography. It aids in flood scope analysis, identifying runoff pollution sources, and predicting changes in runoff geomorphology. The HEC-HMS model is widely used across various fields, including flood management, urban drainage, agricultural planning, forestry, and environmental conservation [8]. It supports numerous

applications such as flood forecasting, watershed and river basin management, climate change impact assessment, and the design of hydraulic structures.
This study used the HEC-HMS version 4.11 to create the hydrologic model and the parameters shown in Table 1 are used to simulate the hydrologic process.

Table 1. Parameters and methods used in the development of the HEC-HMS model

Parameter	Method
Routing	Muskingum-Cunge
Transform	Clark Unit Hydrograph
Loss	Deficit and Constant
Baseflow	Recession Constant

The infiltration calculations in the study utilize the Deficit Constant Loss Method, which considers soil moisture variations for continuous simulation. This approach involves using the Initial Deficit to quantify the water required to saturate the soil initially and the Maximum Deficit to denote the soil's capacity to retain water. Calibration is essential for determining the depth of the active soil layer, and the Constant Rate is used to specify infiltration and percolation rates when the soil is saturated. Impervious areas within the subbasin are identified and do not undergo loss calculations, with all precipitation in these areas considered excess and contributing to surface runoff. Surface runoff calculations are performed using the Clark Unit Hydrograph within the subbasin, utilizing a time-area curve and a linear reservoir for storage attenuation effects. The Time of Concentration and Storage Coefficient are key sub-parameters for this method. Subsurface computations are conducted using the Recession Baseflow Method, which simulates the exponential decrease of baseflow after events and is suitable for both event and continuous simulation. The Muskingum-Cunge method is used for routing, based on the conservation of mass and momentum diffusion, and is updated at each time step according to channel characteristics. HEC-HMS modeling requires four components: the Basin Model prepared in ArcMap, the Meteorological Model specifying precipitation, Time-Series Data for precipitation and discharge, and Control Specifications for simulation start and end times.

After the initial simulation, the user compared the observed and simulated flow rates. Model calibration was performed by adjusting the parameters until the simulated results closely matched the observed data. This calibration process was evaluated through the gaged point in the model. Accurate model calibration is essential in hydrologic modeling studies to minimize simulation uncertainty [9]. The following evaluation statistics are adapted for this study:

Table 2. HEC HMS performance rating (Moriasi et al. 2007, as cited in Santillan, 2019)

Performance Rating	Statistics		
	NSE	PBIAS	RSR
Very Good	0.75<NSE≤1.00	PBIAS < ± 10	0.00 < RSR ≤ 0.50
Good	0.65<NSE≤0.75	±10≤PBIAS < ± 15	0.50 < RSR ≤ 0.60
Satisfactory	0.50<NSE≤0.65	±15≤ PBIAS < ± 25	0.60 < RSR ≤ 0.70
Unsatisfactory	NSE≤0.50	PBIAS ≥ ± 25	RSR > 0.70

The Nash-Sutcliffe efficiency (NSE) measures how well the 1:1 line fits the plot of observed versus simulated data. Percent Bias (PBIAS) evaluates the average tendency of the simulated data to be larger or smaller than their observed counterparts. The RMSE-observations standard deviation ratio (RSR) is determined by the ratio of the RMSE to the standard deviation of the measured data.
After successful model calibration, the model was used to simulate and assess the hydrological condition of the watershed using the historical rainfall records during wet and dry seasons. Wet seasons are from June to November, while dry seasons are from December to May.

2.2 Geologic mapping

The latest available modified lithologic map with lineaments from [10] (after the ones done by UNRFNRE [11]) covering the watershed was utilized for the geologic mapping validation. This was compared with the available geologic map from the Mines and Geosciences Bureau (MGB) and the validated lineaments from the Philippine Institute of Volcanology and Seismology (DOST-PHIVOLCS) in Northern Dinagat Island. However, the updated map generated based on the maps of [10] and [11] were proven to be more detailed and were used as base maps. The team conducted several field surveys simultaneously with the hydrology team for lithologic contact and lineament validation. Rock samples were collected, and the trends of the structures were also measured and noted. The primary sites targeted represent the junction points between at least three rock types (i.e., harzburgite, pillow basalts, sheeted dike complex, and clastic sediments). After validation, the maps were revised and compared with the other obtained data.

3. RESULTS AND DISCUSSION

3.1 Hydrological Assessment

GIS-based Watershed Boundary Delineation

The map of the Sambunotan Watershed with its boundary delineated using IfSAR DTM with the aid of GIS is shown in Fig. 2.

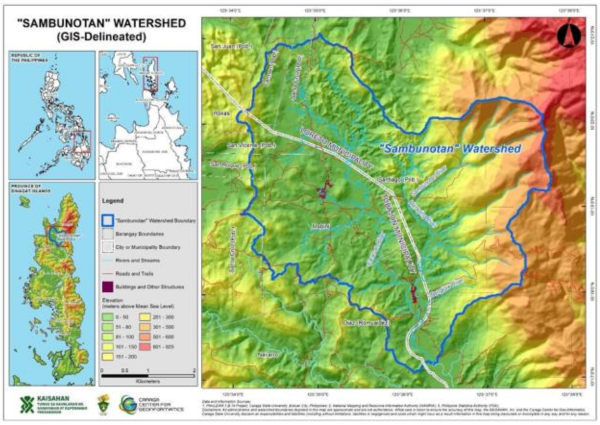

Fig. 2. Map showing the GIS-delineated Sambunotan watershed boundary

Conversely, Fig. 3 compares the DENR-delineated and GIS-delineated watershed boundaries. It can be observed that the differences are mostly located in the ridges. The DENR-delineated boundary appears to have generalized the boundary lines in the ridges, but the GIS-delineated boundary was able to do this more precisely.

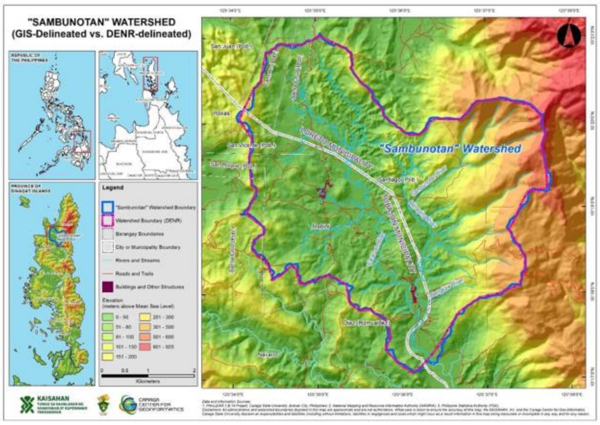

Fig. 3 Comparison of the DENR-delineated and GIS-delineated watershed boundaries.

Based on the GIS-delineated boundary, the watershed lies approximately between $10^0$17’06” to $10^0$21’03” North and $125^0$34’03” to $125^0$37’46” East.

The watershed encompasses the municipalities of Loreto and Tubajon. We found that approximately 63% of the watershed is within the municipality of Loreto, while the remaining 37% is within Tubajon. Three (3) barangays of Loreto and six (6) barangays of Tubajon have administrative boundaries within the watershed. These barangays are Santiago, Santa Cruz, and Carmen in Loreto, and Diaz, Mabini, Santa Cruz, San Roque, San Vicente, and Roxas in Tubajon.

Further analysis revealed that the Sambunotan watershed is a major tributary to a larger watershed, the Malinao Inlet River Basin (Fig. 4). Based on our GIS-aided computations, the watershed occupies approximately 23% of the ~12,277 hectares of Malinao Inlet River Basin. All water coming from the Sambunotan Watershed goes towards the downstream portion of the Malinao Inlet River Basin and towards the Malinao Inlet.

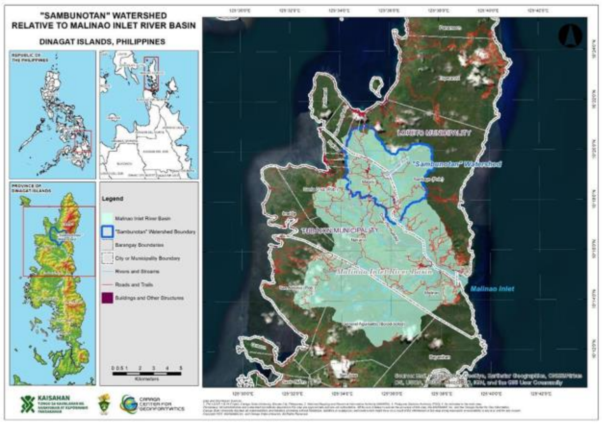

Fig. 4. Map showing that the Sambunotan Watershed is a major part of the larger Malinao Inlet River Basin.

Hydrological Measurements and Modeling

The cross-section profile of the discharge point (facing downstream of the river) was successfully collected (see Fig. 5). The water level collected on the left bank of the river is 0.515 meters, and the lowest elevation of the riverbed is -1.013 meters. The negative elevations imply that these points are below the mean sea level. The average horizontal and vertical root mean square errors of these measurements are 0.0037 meters and 0.0064 meters, respectively.

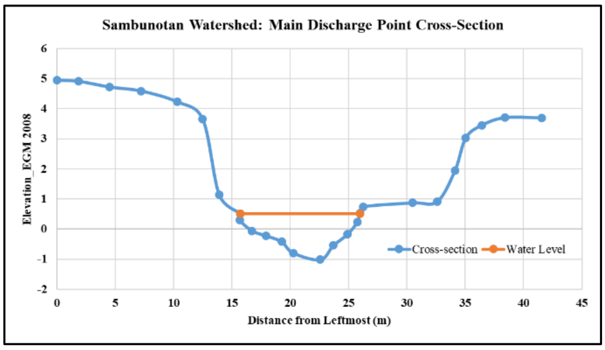

Fig. 5. River cross-section profile and water surface elevation of the discharge point.

Fig. 6, Fig. 7, and Fig. 8 show the results of the hydrological measurements conducted and the relationship between water stage and velocity, water discharge and stage, and water discharge and precipitation, respectively.

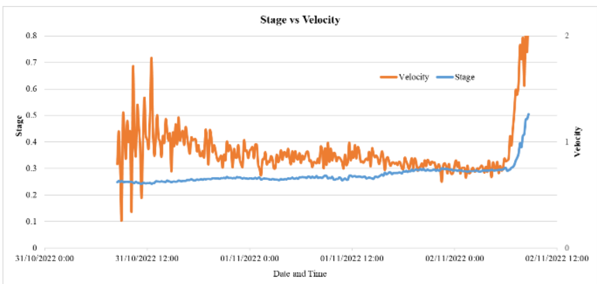

Fig. 6. A graph showing the relationship between the water stage and the velocity.

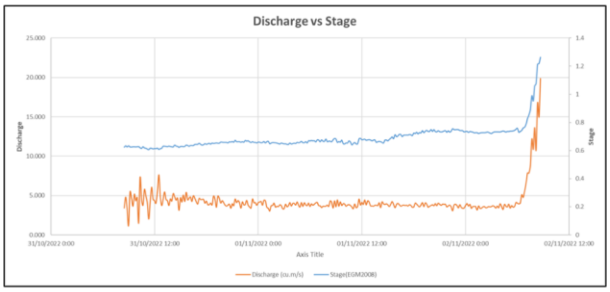

Fig. 7. A graph showing the relationship between water discharge and stage, adopted with permission from [4].

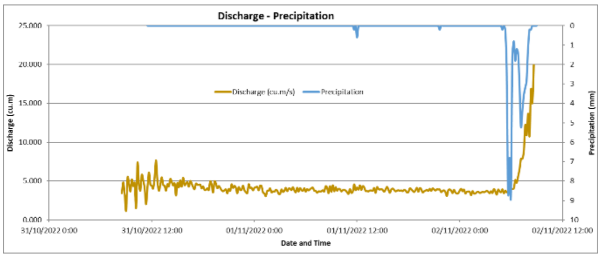

Fig. 8. A graph showing the relationship between water discharge and precipitation.

The hydrologic model of the Sambunotan Watershed (refer to Fig. 9) comprises 48 subbasins, encompassing a total catchment area of 28.2 square kilometers. The discharge point is at coordinates 125°36'21.284"E and 10°17'10.854"N, with an upstream contributing area of 25.23 square kilometers. The basin traverses the municipalities of Loreto and Tubajon in the province of Dinagat Islands.

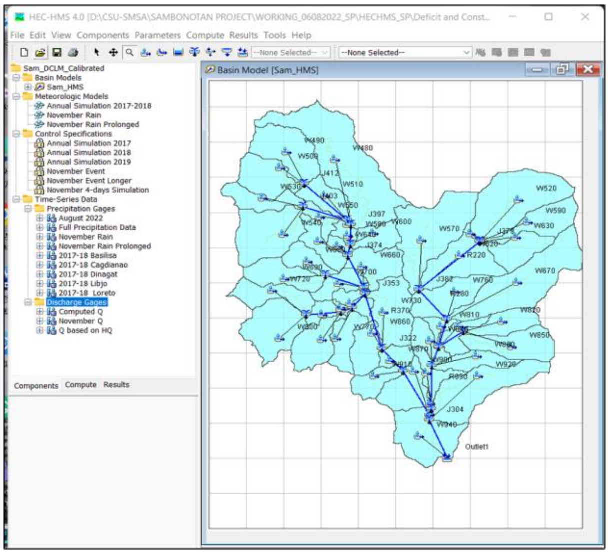

Fig. 9. The Sambunotan watershed hydrological model developed in HEC-HMS, adopted with permission from [4].

The model calibration employed actual field data collected in November 2022, and the calibration period spanned from October 31, 2022, at 15:50 to November 2, 2022. Figure 10 illustrates the pre-calibration model, where the simulated values (blue) did not peak or match the observed values (black). As a result, calibration was necessary to align the simulated values with the observed data, as shown in Fig. 11.

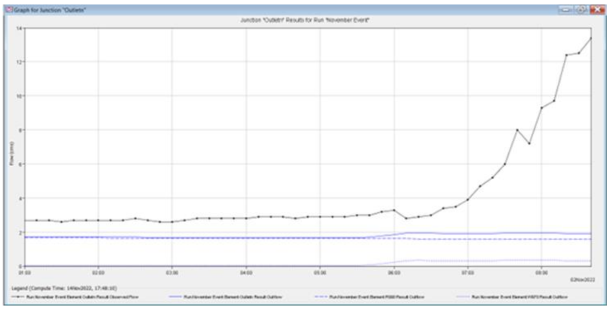

Fig. 10. Pre-calibration result at Discharge Point, adopted with permission from [4].

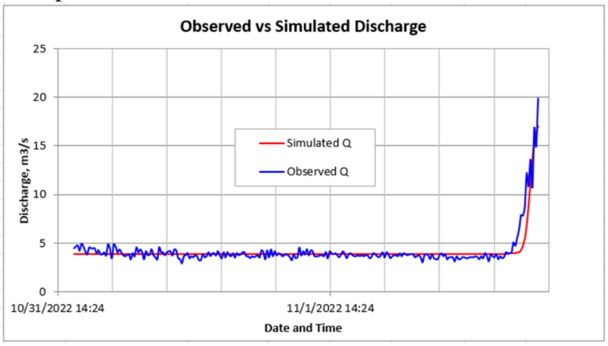

Fig. 11. Calibration results at calibration/discharge point, adopted with permission from [4].

Table 3 below shows the calibrated models' overall rating of "Very Good."

Table 3. Performance evaluation results after calibration

Statistics/Rating	Computed Error
NSE	0.85
RSR	0.38
PBIAS	1.62
Overall Rating	Very Good

Total rainfall of 1,297.21mm was recorded during the dry season, specifically from December 2017 to May 2018. While 4,953.07mm was recorded during the wet season from June 2018 to November 2018. Using these recorded rainfall data as input in the hydrologic model, the computed annual baseflow volume is 71,601,871.66 m^3 (see Table 4). As expected, the baseflow during the wet season is higher than in the dry season.

Table 4. Computed baseflow volume

Sub watershed	Dry (Baseflow Volume, m^3)	Wet (Baseflow Volume, m^3)	Baseflow Volume (m^3)
	December to May	*June to November*	*Total*
Sambunotan	751,888.95	4,968,604.63	5,720,493.58
Maraging	9,937,849.23	18,580,501.84	28,518,351.07
Carac-an	8,086,171.49	28,422,732.85	36,508,904.35
Bangkaw	57,266.71	711,444.22	768,710.93
Others	3,506.82	81,904.91	85,411.73
Total	**8,836,683.21**	**52,765,188.45**	**71,601,871.66**

3.2 Geologic Mapping

Drainage Network Analysis

A revised geologic map for the study area was constructed based on the aggregate data from the previous map sources [10, 11] and the ones collected from the field, as shown in Figs. 12 and 13.

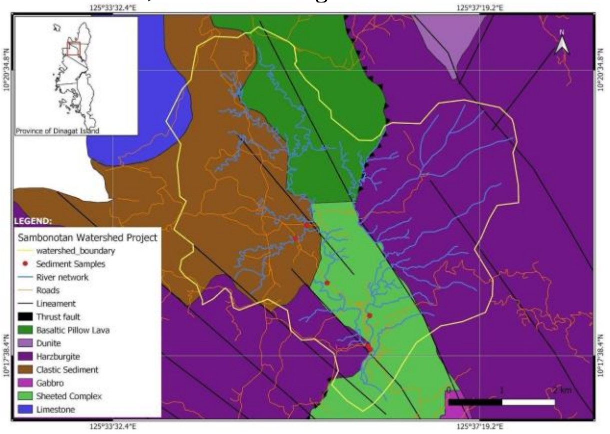

Fig. 12. Revised geologic map of the Sambunotan Watershed showing the different lithologies within the study area (i.e., harzburgite (purple), sheeted dike complex (light green), pillow basalts (green) and clastic sediments (brown).

Fig. 13. One of the lithologic contacts observed in the field between harzburgite (harz) and basalt (bas) lithologies. Structures (red lines) such as faults and veining were also noted.

A highlighted portion of the revised lithologic map is shown in Fig. 14. One of the key results of the geologic mapping is validating the major river network within the watershed as structurally controlled. This means that the river networks are formed probably because of the lineament cutting the island, and/or they are a consequence of the contact between two different rock types. The planes of weaknesses brought about by lithologic contacts, or the lineament structures, are usually the regions where water tends to flow.

The relationship between the river network and the geological characteristics of the area is further emphasized by the topography and slope. Fig. 15 shows the heavy influence of the lithologic variations in the area on the consequent terrain in the watershed. The ridges and mountains in the eastern portion of the study area coincided with the harzburgite region found within the region. The rolling hills observed in the central portion of the watershed remarkably correspond with the crustal rocks mapped (i.e., sheeted dike complex, pillow basalts). A relatively flat terrain is observed for the areas of the sedimentary rocks (i.e., clastic sediments).

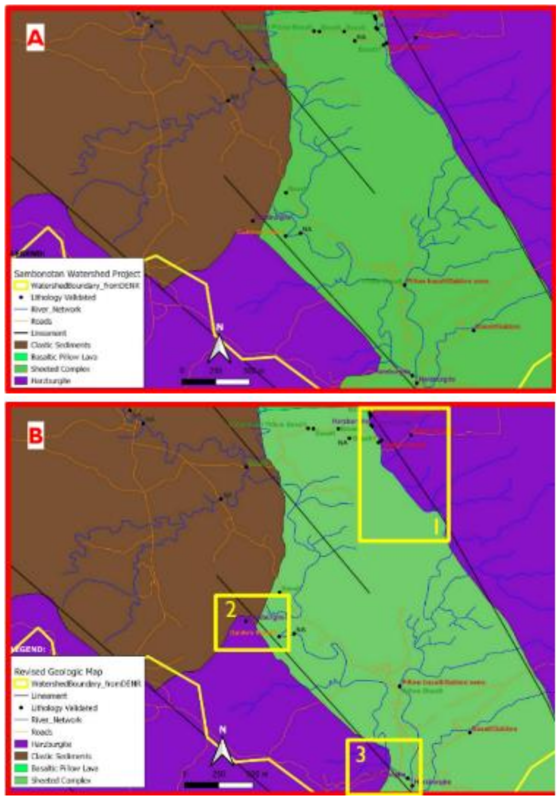

Fig. 14. Highlighted portion of the revised geologic map of the Sambunotan Watershed showing you some of the changes made on the previous map as observed from the field (A. before validation; B. after validation). Yellow box 1 shows the portions of the Maraging River as structurally controlled by the lineament running along it. Yellow boxes 2 and 3 represent the extension of the harzburgite zones northward and eastward, respectively.

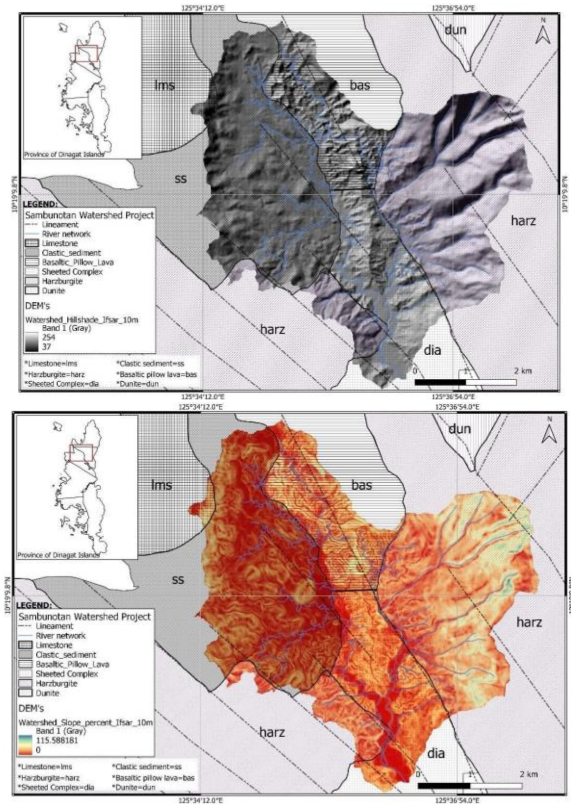

Fig. 15. Revised geologic map overlain on the topography (top) and slope map (bottom) within the watershed.

Potential Groundwater Resources Location

Extending the coverage of the lithologic map outside the watershed boundary and overlaying the water resource location map of the two municipalities (e.g., Tubajon and Loreto can provide clues on the possible groundwater resources in the area (Fig. 16). Among the rock types found in northern Dinagat, the regions of the limestone (blue region) and clastic sediments (brown region) are shown in Fig. 16. have the highest potential to become aquifers based on the high porosity and permeability of these units [12]. Clastic sediments, especially if described as medium to very coarse-grained sandstones, will be a more viable option for groundwater resource exploration among the two lithologies. This is validated by the concentration of most of the water resources of the two municipalities in these two rock types. The municipalities of Tubajon and Loreto can further focus their resources in these two regions if they wish to go the groundwater exploration route. A more robust lithologic study must be done to characterize these two units' aquifer potential fully. Also, further validation of the water resources found in igneous bodies (i.e., basalts, sheeted complex, harzburgite, and dunite) must be conducted to assess the water resource characteristics.

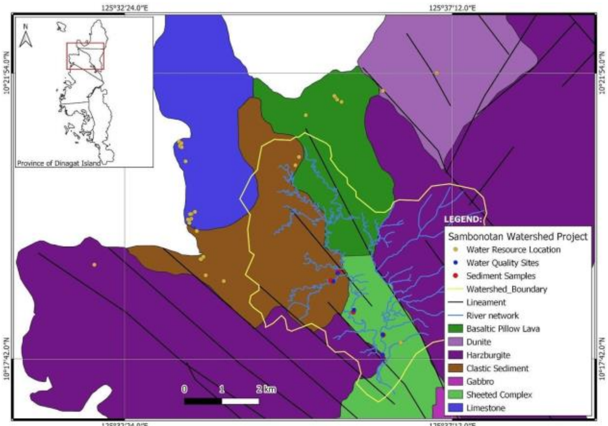

Fig. 16. Location of the two municipalities' water resources (yellow dots) overlaid on top of the revised lithologic map.

4. CONCLUSIONS

In summary, the combined hydrological and geological assessments of the Sambunotan Watershed have revealed several key findings essential for sustainable watershed management.

Utilizing GIS tools and IfSAR DTM, a precise boundary of the Sambunotan Watershed was delineated, covering 2,819.9125 hectares. This watershed is primarily situated within the municipalities of Loreto (63%) and Tubajon (37%) and forms a significant part of the larger Malinao Inlet River Basin.

The hydrological modeling using the HEC-HMS model, calibrated with actual field data, achieved a "Very Good" performance rating. The model simulation indicated a total annual baseflow volume of 71,601,871.66 m^3. As expected, the baseflow during the wet season is higher than in the dry season, contributing to around 73.69% of the annual baseflow (52,765,188.45 m^3 versus 8,836,683.21 m^3).

The revised geological map illustrated that the watershed's river networks are lithologically and structurally controlled, with significant influences from harzburgite and basalt rocks. Field surveys validated the presence of various lithologies, including harzburgite, pillow basalts, and clastic sediments. The analysis confirmed that the river networks align with geological structures and lithologic contacts, significantly impacting the watershed’s hydrology. The study identified regions with clastic sediments and limestone as potential aquifers due to their high porosity and permeability. These areas are recommended for further groundwater exploration to support local water needs.

The combined hydrological and geological study conducted in this research directly supports the development of the Sambunotan Watershed Management Plan. The datasets and information, including the hydrological model simulated results, and geologic characteristics, can satisfy the needed baseline information required in developing the watershed management plan.

The combined hydrological and geological study conducted in this research directly supports the development of the Sambunotan Watershed Management Plan. Geological assessment enhances and supports the hydrological findings by providing a better understanding of the watershed's dynamics. The datasets and information, including the hydrological model's simulated results and the geologic characteristics, offer essential baseline data crucial for developing effective and sustainable management strategies for the watershed. This integrated approach ensures the protection and optimal use of the Sambunotan Watershed's resources.

5. ACKNOWLEDGMENT

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